# Study of calibration of Windsat polarimetric sensor

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*Abstract*- **A new methodology is developed to monitor and calibrate the Windsat 3rd and 4th Stokes parameters through tropical rainforest measurements over Amazon and the central Africa. It is found that the Windsat 4th Stokes parameter at 18 GHz has biases on an order of 0.5 Kelvin, which could severely impact the wind vector retrievals.**

## I. INTRODUCTION

The first passive polarimetric microwave sensor, Windsat was launched onboard the Navy Coriolis satellite on January 6, 2003. Windsat has a dual polarization at 6.8 and 23.8 GHz, and fully polarimetric observations at 10.7, 18.7 and 37 GHz. The dual polarization measurements at 6.8 GHz are mainly used for studying soil moisture and sea surface temperature, while those at 23.8 GHz are primarily used for determining total amount of atmospheric water vapor in the vertical column. The polarimetric measurements at other frequencies are developed for obtaining the surface wind velocity over the oceans. Windsat's new capabilities will be extremely useful in improving weather predictions for systems formed over open water that are less observed by conventional instruments.

This study investigates the instrumental bias for the passive polarimetric sensor. The instrumental bias is one of the most important factors affecting the satellite data assimilations in the numerical weather prediction model. To monitor and to obtain accurate radiance measurements, both pre-launch [1] and post-launch calibration are important. In the pre-launch stage, the thermal-vacuum chamber calibration data can be analyzed to evaluate the instrumental performance including calibration accuracy and nonlinearity as well as the sensor noise. The fundamental objective of the vicarious or post-launch calibration is to adjust the effects of sensor's systematic gain offset and degrading. The adjustment may be accomplished by the radiative transfer calculations using in-situ measurements of geophysical parameters or by known standard source such as moon light for visible and near infrared bands. In this study, we choose tropical rainforest as a standard target for the vicarious calibration of the 3rd and 4th Stokes parameters of Windsat.

## II. DESCRIPTION OF DATA

The Windsat data used in this study covers a period from September 2003 to February 2004. Windsat delivers Stokes parameters [2]. All Stokes parameters have the same unit, and all of them are observable. The first Stokes parameter (intensity) is the sum of the vertical and horizontal linearly polarized components. The second Stokes parameter (polarization difference) refers to the intensity difference between the vertical and horizontal linearly polarized components. The 3rd Stokes parameter (plane of polarization) measures the difference in intensities between linearly polarized components oriented at +45º and -45º. The 4th Stokes parameter (ellipticity) is defined as the difference in intensities between right- and left-circularly polarized components. Windsat measures the above six components to reconstruct the Stokes parameters. These parameters vary with ocean wind direction with an amplitude of a few Kelvin [3], a consequence of the electromagnetic waves (EM) scattered by ocean waves having large (gravity) and small (capillary) scales. There is a typical phase shift between the 3rd and 4th parameters, as predicted by the two-scale scattering model, which is a primary signature for determining the sea surface wind direction.

The Windsat instrument is calibrated with two targets: one cold space temperature observed by a sub-reflector, and another thermal source observed by the main reflector. Due to the environmental change between pre- and post-launch, and the degradation of instruments, vicarious calibration and noise estimate for the 3rd and the 4th Stokes parameters are necessary. The Windsat calibration and validation science team has shown that Windsat's six polarization

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channels are calibrated with an accuracy better than the Special Sensor Microwave/Imager, and a noise equivalent standard temperature (NEDT) of about 0.4 Kelvin [2]. Given the fact that the 4$^{th}$ Stokes parameter refers to a difference between the left- and right-circularly polarized measurements, one would expect larger NEDT at the 4$^{th}$ Stokes parameter if the noises of two circular polarizations are uncorrelated. Such a magnitude could have severely downgraded usage of Windsat data for wind vector retrievals. Actual NEDT is fortunately smaller by averaging samples and by the partial correlation of polarizations.

## III. METHODOLOGY

The 3$^{rd}$ and 4$^{th}$ Stokes parameters are designed for the determination of the sea surface wind direction. The ocean surface emissivity at the 3$^{rd}$ and 4$^{th}$ Stokes parameters can be well described by two harmonic sine functions of the wind direction [3]. Therefore, the mean value or the integration over azimuth angles is zero under same atmospheric conditions. However, the ocean surface apparently displays regional wind zones like eastward wind in sub-tropic zones. The behavior complicates using the zero mean value over oceans for the purpose of the vicarious calibration. The tropical rainforest covers with very dense canopy. The canopy absorbs the most of the surface radiation so that there are no 3$^{rd}$ and 4$^{th}$ signatures from the rainforest, in general. Residual signature at 3$^{rd}$ may be observed due to the oriented leaves and inhomogeneous clouds. The 4$^{th}$ Stokes parameter wouldn't be generated from the geometric orientation of leaves and the inhomogeneous clouds of spherical particles. Thus, the tropical rainforest can serve as a place for the vicarious calibration of 3$^{rd}$ and in particular for the 4$^{th}$ Stokes parameters.

To investigate the noise, we analyze Windsat data over the Amazon and Central African regions, and vicariously estimate the noise amplitudes. Amazon and Central Africa are covered by warm and dense tropical rain forests. At Windsat frequencies, surface radiation is attenuated by leaves, and the satellite observations are characterized by forest canopy. If the 4$^{th}$ Stokes parameter is assumed to be zero, the mean value away from zero can be treated as an instrumental bias, and its standard deviation represents the noise. Three-dimensional radiative effects from ice and raining clouds may result in a small residual error for the 3$^{rd}$ Stokes parameter. Even for clouds having spherical particles, the contribution to the 3$^{rd}$ Stokes parameter could result in a few degrees (in Kelvin) at 10.7 GHz. Tables 1-3 show the monthly mean and standard deviation of the 3$^{rd}$ and 4$^{th}$ Stokes parameters of Windsat measurements from September 2003 to February 2004. It is shown that the measurements from Amazon and African rainforests display similar features, and the results there support our above assumption on the 4$^{th}$ Stokes parameter over rainforests. The onboard calibration at 37 GHz is quite good with negligible bias and its standard deviation of about 0.05 Kelvin, which is much smaller than the individual noise at linear and circular polarizations (0.4 Kelvin). The standard deviation of the 4$^{th}$ Stokes parameter at 18.7 GHz is about 0.1 Kelvin, much smaller than individual noise at circular polarizations (see Table 2). However, the mean value of about -0.56 Kelvin for the 4$^{th}$ Stokes parameter in Table 2 corresponds to a bias resulting from calibration errors in the circularly polarized measurements. Table 3 shows that the onboard calibration at 10.7 GHz is fine, with a standard deviation is about 0.1 Kelvin. Figure 1 shows the time series of the 4$^{th}$ Stokes parameter mean value over the Amazon rainforest. These data points are sparse, because the revisit time of the Windsat data is about 8 days. The mean values at 10.7 GHz (diamond) and 37 GHz (square) are close to zero, while the mean value at 18.7 GHz (triangle) is apparently biased. The standard deviation of the 4$^{th}$ Stokes parameter is about 0.1 Kelvin (see Fig. 2), representing the parameter noise. The noise level of 0.1 K for the 4$^{th}$ Stokes parameter is tolerable for the retrieval of the sea wind direction,[4] but the bias at 18.7 GHz has to be corrected.

## IIII. CONCLUSION

Tropical rainforest over Amazon and central Africa is found to be a place for the vicarious calibration of the polarimetric sensor of Windsat. Analysis results over a period of 6 months show the radiometric noise of Windsat at the 3$^{rd}$ and 4$^{th}$ Stokes parameters is generally below 0.1 Kelvin. the Windsat 4$^{th}$ Stokes parameter at 18 GHz has biases on an order of 0.5 Kelvin, which could severely impact the wind vector retrievals.

**Table 1.** Monthly mean and standard deviation of the 3rd and the 4th Stokes parameters at 37 GHz over Amazon and African rainforests.

| Month | Amazon | | | | Central Africa | | | |
|---|---|---|---|---|---|---|---|---|
| | Third Stokes Parameter | | Fourth Stokes Parameter | | Third Stokes Parameter | | Fourth Stokes Parameter | |
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation | mean | Standard deviation |
| Sep. 2003 | -0.074 | 0.071 | -0.041 | 0.061 | -0.075 | 0.085 | -0.042 | 0.062 |
| Oct. 2003 | -0.060 | 0.074 | -0.031 | 0.059 | -0.070 | 0.080 | -0.025 | 0.066 |
| Nov. 2003 | -0.059 | 0.079 | -0.035 | 0.060 | -0.068 | 0.074 | -0.036 | 0.068 |
| Dec. 2003 | -0.065 | 0.083 | -0.033 | 0.059 | -0.072 | 0.080 | -0.030 | 0.061 |
| Jan. 2004 | -0.059 | 0.083 | -0.033 | 0.062 | -0.063 | 0.087 | -0.041 | 0.061 |
| Feb. 2004 | -0.065 | 0.074 | -0.028 | 0.062 | -0.067 | 0.086 | -0.041 | 0.065 |

**Table 2.** Same as Table 1, but at 18.7 GHz.

| Month | Amazon | | | | Central Africa | | | |
|---|---|---|---|---|---|---|---|---|
| | Third Stokes Parameter | | Fourth Stokes Parameter | | Third Stokes Parameter | | Fourth Stokes Parameter | |
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation | mean | Standard deviation |
| Sep. 2003 | 0.220 | 0.268 | -0.568 | 0.102 | 0.230 | 0.264 | -0.561 | 0.114 |
| Oct. 2003 | 0.202 | 0.268 | -0.562 | 0.103 | 0.205 | 0.247 | -0.568 | 0.115 |
| Nov. 2003 | 0.219 | 0.270 | -0.561 | 0.108 | 0.223 | 0.236 | -0.568 | 0.114 |
| Dec. 2003 | 0.249 | 0.293 | -0.560 | 0.110 | 0.272 | 0.293 | -0.564 | 0.122 |
| Jan. 2004 | 0.233 | 0.285 | -0.552 | 0.105 | 0.238 | 0.271 | -0.560 | 0.115 |
| Feb. 2004 | 0.227 | 0.278 | -0.565 | 0.105 | 0.227 | 0.290 | -0.564 | 0.111 |

**Table 3.** Same as Table 1, but at 10.7 GHz.

| Month | Amazon | | | | Central Africa | | | |
|---|---|---|---|---|---|---|---|---|
| | Third Stokes Parameter | | Fourth Stokes Parameter | | Third Stokes Parameter | | Fourth Stokes Parameter | |
| | mean | Standard deviation | mean | Standard deviation | Mean | Standard deviation | mean | Standard deviation |
| Sep. 2003 | -0.204 | 0.193 | -0.021 | 0.102 | -0.198 | 0.187 | -0.022 | 0.099 |
| Oct. 2003 | -0.181 | 0.199 | -0.053 | 0.102 | -0.194 | 0.196 | -0.049 | 0.098 |
| Nov. 2003 | -0.197 | 0.202 | -0.026 | 0.101 | -0.227 | 0.199 | -0.015 | 0.099 |
| Dec. 2003 | -0.207 | 0.203 | 0.001 | 0.103 | -0.190 | 0.196 | 0.011 | 0.103 |
| Jan. 2004 | -0.189 | 0.203 | -0.007 | 0.103 | -0.214 | 0.209 | -0.001 | 0.098 |
| Feb. 2004 | -0.184 | 0.205 | -0.036 | 0.103 | -0.185 | 0.206 | -0.035 | 0.103 |

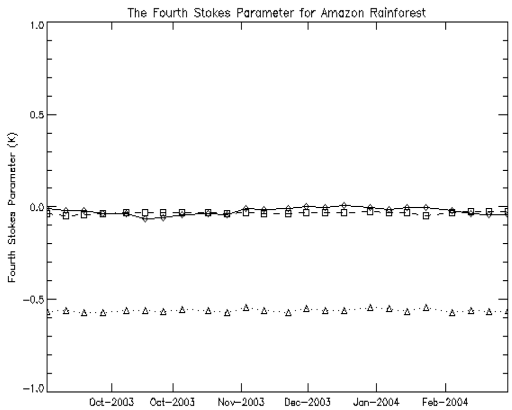


**Figure 1.** Time series of the mean 4th Stokes parameter over Amazon rainforests. The lines with diamond, triangle and square correspond to 10.7, 18.7 and 37 GHz, respectively

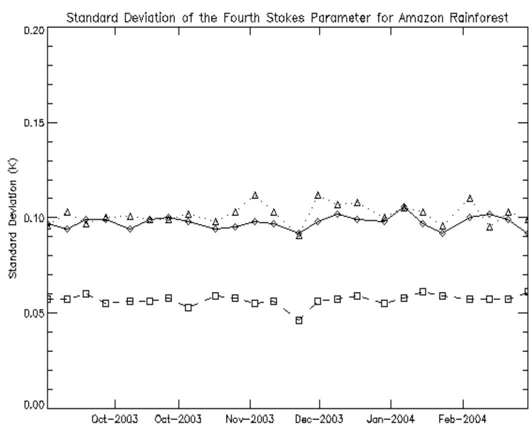


**Figure 2**. Time series of the standard deviations (or noise) of 4th Stokes parameter over Amazon rainforests. The lines with diamond, triangle and square correspond to 10.7, 18.7 and 37 GHz, respectively.

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